

THE AGES OF ELLIPTICAL GALAXIES FROM INFRARED SPECTRAL ENERGY DISTRIBUTIONS

JOEL N. BREGMAN¹, PASQUALE TEMI^{2,3,4}, AND JESSE D. BREGMAN²

Draft version February 5, 2008

ABSTRACT

The mean ages of early-type galaxies obtained from the analysis of optical spectra, give a mean age of 8 Gyr at $z = 0$, with 40% being younger than 6 Gyr. Independent age determinations are possible by using infrared spectra (5–21 μm), which we have obtained with the Infrared Spectrograph on the Spitzer Observatory. This age indicator is based on the collective mass loss rate of stars, where mass loss from AGB stars produces a silicate emission feature at 9–12 μm . This feature decreases more rapidly than the shorter wavelength continuum as a stellar population ages, providing an age indicator. From observations of 30 nearby early-type galaxies, 29 show a spectral energy distribution dominated by stars and one has significant emission from the ISM and is excluded. The infrared age indicators for the 29 galaxies show them all to be old, with a mean age of about 10 Gyr and a standard deviation of only a few Gyr. This is consistent with the ages inferred from the values of M/L_B , but is inconsistent with the ages derived from the optical line indices, which can be much younger. All of these age indicators are luminosity-weighted and should be correlated, even if multiple-age components are considered. The inconsistency indicates that there is a significant problem with either the infrared and the M/L_B ages, which agree, or with the ages inferred from the optical absorption lines.

Subject headings: Galaxies: Elliptical and Lenticular, Galaxies: ISM, Infrared: Galaxies, Infrared: ISM

1. INTRODUCTION

Prior to the acceptance of the hierarchical paradigm for structure formation, monolithic collapse was proposed for the formation of ellipticals and spheroids. In the monolithic model, an elliptical would form at high redshift from a gas cloud that produced a brief but intense epoch of star formation when most of the stars were formed. A subsequent galactic wind could keep the galaxy gas poor for most of its life, preventing the accumulation of gas that could lead to ongoing star formation. This picture was in good agreement with the data (Pipino & Matteucci 2003, 2005), yet modern theories of hierarchical structure formation indicate that mergers should be important through cosmological time (e.g., Kauffmann & Charlot 1998). In the case of elliptical galaxies, this meant that existing galaxies would merge to form larger ones, with accretion possibly triggering a burst of star formation in the cold gas in these galaxies. If nearly all of the star formation were to occur early, it would imply important changes to the basic hierarchical model, so it is essential to have good knowledge for the age of elliptical galaxies.

Stellar ensembles that are less than 2 Gyr in age show prominent A or F star features, enabling unique age determinations. However, once the age of the system is a few Gyr, the colors and metal line strengths of the galaxy do not lead to a unique age because of a degeneracy between the metallicity and age parameters. That is, an old metal-poor galaxy will have the same colors

and metal line strengths as a younger metal-rich galaxy. To break this age-metallicity degeneracy, investigators measure the strength of the Balmer lines (notably $H\beta$; dominated by turnoff stars) along with a variety of metal line indexes in the spectrum of a galaxy (due to AGB stars), which they compare to models (Worthey 1994; Worthey et al. 1994). There are a number of effects that can contaminate the age-dating, but Trager et al. (2000) discuss the most likely candidates and argue that they are unlikely to cause problems. It would seem that this method should give a good estimate for the mean age of a single population.

Trager et al. (2000) find that for stars within $r_e/2$, the metallicities are generally near-solar and with a small range of abundance enhancements. The ages, however, show a much broader range, with a median value of 7–8 Gyr and nearly 40% of the galaxies with ages of 6 Gyr or less. These relatively young ages correspond to a median redshift of about 1, with about a 40% of the sample having formed at $z < 0.6$. This supports the hierarchical model with recent merging events. Whereas some mergers are observed today, current surveys suggest that most of the stellar populations in elliptical galaxies have been evolving passively since at least $z \sim 1$. This is in apparent conflict with the age distribution of Trager, so either their approach has unanticipated flaws, or multiple populations conspire to produce the observed ages. To help resolve this possible conflict, an independent age estimator is required, and the development of such a tool is the purpose of this paper.

2. INFRARED SPECTRAL ENERGY DISTRIBUTIONS AS AGE INDICATORS

The optical age-dating technique makes use of absorption lines that are produced in the photospheres of stars, generally at the turnoff and on the giant branch. In contrast, the infrared signature that we will use is produced in the outflow of mass-losing giants, and in particular,

¹ Astronomy Department, University of Michigan, Ann Arbor, MI 48109

² Astrophysics Branch, NASA Ames Research Center, MS 245-6, Moffett Field, CA 94035

³ SETI Institute, 515 N. Whisman Road, Mountain View, CA 94043.

⁴ Department of Physics and Astronomy, University of Western Ontario, London, Ontario, N6A 3K7, Canada.

the asymptotic giant branch stars. Asymptotic giant stars have very substantial slow winds, within which the density is large enough for material to condense, leading to grain formation. Silicates are common and they are formed close enough to the star to be heated to $\sim 300\text{K}$. These silicates reradiate in a few broad regions, such as $9\text{--}12\ \mu\text{m}$ and another centered near $18\ \mu\text{m}$. At shorter wavelengths ($6\ \mu\text{m}$), the continuum is produced close to the stellar photosphere, so the $5\text{--}21\ \mu\text{m}$ region contains both circumstellar emission and near-photospheric emission.

As an ensemble of stars age, the overall luminosity of the population decreases roughly as t^{-1} , so it might seem that the best measure of age would be the mass-to-light ratio. However, the mass is the sum of the stellar component and the dark matter component, and one must have confidence that the stellar component dominates this ratio in the region it is measured. Alternatively, one can seek to find spectral features that have different time dependencies, so that their ratios change monotonically with time. For example, models indicate that the $6\ \mu\text{m}$ luminosity density decreases as $t^{-0.77}$ in solar-type populations (Figure 1), while the emission from the silicate mass loss decreases more rapidly, as $t^{-1.09}$ ($9.6\ \mu\text{m}$ luminosity density). The ratio $L(9.6\ \mu\text{m})/L(6\ \mu\text{m}) \propto t^{-0.32}$, so there is a mapping from this ratio to the mean age of the stellar population.

To calibrate this method, one can appeal either to models or to stellar systems whose metallicity and age are known. Eventually, we hope to apply the latter method, but for this study, we used stellar evolutionary models. Only recently have stellar evolutionary models included the observable consequences of mass loss from AGB stars (Bressan et al. 1998; Lançon & Mouhcine 2002; Mouhcine & Lançon 2003) and here we use the models developed by Piovan et al. (2003). They have produced detailed spectral energy distributions from $0.1\text{--}100\ \mu\text{m}$ for a single population of stars at a sequence of ages and for three different metallicities, including the Solar value ($Z = 0.02$), used here. Their models include the effects of dust-enshrouded AGB stars, with emission from silicates, carbon, and silicon carbide, the latter two being important in massive stars.

We have analyzed their models, made available for use by the authors, to determine the most suitable infrared indices that can act as an age indicator over the wavelength region for which we have data, $5.2\text{--}21\ \mu\text{m}$. We find that the spectral slope, $d\ln F_\nu/d\ln \nu$, from $5.2\text{--}6.5\ \mu\text{m}$ is a useful age indicator, as it steepens from about -0.27 at $2\ \text{Gyr}$ to -1.07 at $16\ \text{Gyr}$ (Figure 2). There is scatter around this relationship due to the finite number of stellar models used in the calculations. That is, stellar models are calculated for every $0.1\ M_\odot$ near values of $1\ M_\odot$, and the turnoff ages are $9.3\ \text{Gyr}$ for a $1\ M_\odot$ star, $6.5\ \text{Gyr}$ for a $1.1\ M_\odot$ star, and $4.5\ \text{Gyr}$ for a $1.2\ M_\odot$ star. Not only do the relative state of the core and envelope change in this mass range, but the dust properties change as well, so the change in the relative fractions of these stellar components can cause the observed non-smooth behavior in the $6\ \mu\text{m}$ slope (this is also true of the flux ratios that we will use). Consequently, we have fit a smooth line through these model points (Figure 2).

Aside from this slope, one can use the luminosities at $6\ \mu\text{m}$ (from the power-law fitting to the $5.2\text{--}6.5\ \mu\text{m}$ con-

tinuum), the luminosity at the local minimum of $8.3\ \mu\text{m}$ (averaged $8.0\text{--}8.5\ \mu\text{m}$), and a luminosity at $9.6\ \mu\text{m}$ (averaged over $9.2\text{--}10.0$ that measures the silicate excess). Of the ratios that can be formed with these luminosities, the $L(9.6\ \mu\text{m})/L(6\ \mu\text{m})$ and $L(6\ \mu\text{m})/L(8.3\ \mu\text{m})$ quantities are the best tracers of age. Another age indicator can be formed by using a luminosity at longer wavelength $L(14\ \mu\text{m})$, compared to $L(6\ \mu\text{m})$. The boundaries of these luminosities were chosen to avoid possible PAH bands (strongest at $7.7\ \mu\text{m}$, $11.3\ \mu\text{m}$), although PAH emission is rarely seen in the galaxies we observed. For the following analysis, we will primarily use $L(9.6\ \mu\text{m})/L(6\ \mu\text{m})$, as it has the greatest range and the smallest relative uncertainty. The mapping between this ratio and the age is $t = 2.6 (L(9.6\ \mu\text{m})/L(6\ \mu\text{m}))^{-3.1}\ \text{Gyr}$.

The models of Piovan are the first at this level of detail and cannot be expected to be perfect, so the absolute calibration of the models may be somewhat incorrect. However, the relative trend should be reliable in identifying old and young systems.

3. SAMPLE SELECTION AND OBSERVATIONAL PROGRAM

Our sample is taken from a survey of 51 nearby ellipticals for which high-quality optical spectra were obtained (Trager et al. 2000, and references therein). Although ages derived from absorption line indices have uncertainties associated with the adopted stellar models and patterns of abundances when alpha-enhanced mixtures are adopted (Tantalo & Chiosi 2004), these galaxies have well established age-metallicity determinations among nearby elliptical galaxies. Others have determined ages for nearby ellipticals (summary by Terlevich & Forbes 2002; recent determinations by Thomas et al. 2005a), which are similar and are discussed further below.

From the Trager et al. (2000) sample, we have taken a subset of galaxies with the properties: $B_{0T} < 12.5$; $M_B < -19$ (no dwarfs); and no AGN activity (two 3C objects are excluded). This leads to a well-defined sample of 31 galaxies covering a broad range of implied ages, from $2\ \text{Gyr}$ to $15\ \text{Gyr}$, with a fairly even distribution by age: 8 galaxies have estimated ages of $2\text{--}5\ \text{Gyr}$, 7 are between $5\text{--}8\ \text{Gyr}$, 9 are between $8\text{--}12\ \text{Gyr}$, and 7 are between $12\text{--}18\ \text{Gyr}$ (Table 1; the metallicity Z_H and ages are within $r_e/8$ as given in Trager et al. 2000). The mean iron metallicity for the sample is $[\text{Fe}/\text{H}] = 0.06$ and the 25/75% quartiles are -0.04 to 0.15 , so the range is modest. This sample is representative of elliptical galaxies with optical luminosities near L_* . For one galaxy, NGC 3608, there were significant instrumental difficulties and the resulting data are not reliable, so it is not included. For one other galaxy, NGC 4697, the spectrum is completely different than the rest, is not useful for age determinations, and will be discussed elsewhere.

Based on the spectral model of Piovan (and observational data of AGB stars), it is important to define both the underlying continuum as well as the silicate feature, and this requires spectroscopic coverage from about $5\text{--}20\ \mu\text{m}$. This type of coverage was realized with the combination of Short-Low, and Long-Low modules on the Infrared Spectrograph (IRS; Houck et al. 2004) on board the *Spitzer Space Telescope* (Werner et al. 2004). These modules together provide spectral coverage of the region $5.2\text{--}21.3\ \mu\text{m}$ with a spectral resolution $R = \lambda/\Delta\lambda$ of 64--

128, depending on the wavelength. Both segments of the Short-Low spectral region ($5.2\text{--}7.7\text{ }\mu\text{m}$ for the SL2 module, $7.4\text{--}14.5\text{ }\mu\text{m}$ for the SL1 module) use the same slit size ($3.7''$ by $57''$) and position angle, but the Long-Low ($14.0\text{--}21.3\text{ }\mu\text{m}$ for the LL2 module) slit is $10.5''$ by $168''$ and is at a position angle about 90° different than the Short-Low. In this case, we will match the spectra by using the overlap region at $14\text{ }\mu\text{m}$.

The galaxies are not point sources, but are well-contained within the slits as the typical half-light radius is $30''$. In the IRS staring mode, two spectra were obtained per setting, with each offset from the center of the slit by one third of a slit length. This results in the endpoint of the Short-Low slit in the off position is $38''$ from the center of the galaxies where the galaxy signal is about 2% of the signal at the center, or 0.2 mJy on average (much smaller than the measured signals). For the Long-Low, the offset is much greater, so the contribution from the galaxy in the off position is negligible. The integration time for each galaxy is the same, consisting of 8 cycles of 14 sec ramp time for Short-Low and 6 cycles at 30 sec for Long-Low.

4. DATA PROCESSING

The standard IRS data reduction pipeline, version S12.0, at the Spitzer Science Center (SSC) was used to reduce the data. This reduction includes ramp fitting, dark-sky subtraction, droop correction, linearity correction, flat-fielding, and wavelength and flux calibration (Decin et al. 2004). Before performing the spectral extraction, the local background for the SL modules was subtracted using observations when the target was located in an alternate slit. At longer wavelengths, since we recorded data using only the LL2 module, the local background was subtracted by differencing the two nod positions along the slit. The spectra were then extracted from the sky-subtracted two-dimensional array images using the SMART (ver. 5.5.6) software package (Higdon et al. 2004), after the mean of the flux estimates from each ramp cycle were combined. We performed a "fixed column extraction" because the emission from each galaxy did not resemble the point source profile, showing substantial extended emission. In its current form, the SMART software is optimized to perform spectral extraction and flux calibration for point source targets. In order to correct for the use of the standard flux conversion tables, which are based on point source extraction, we applied a correction that accounts for the aperture loss due to the narrowing of the extracting column as a function of wavelength used by SSC and that in turn feeds back into the FLUXCON tables. Observations of the standard star HR 6348 were used to calibrate our target spectra. A spectrum of HR 6348 was constructed combining a number of observations recorded in 2004 under the program ID 1404. Our spectra were calibrated by dividing the extracted spectrum of the source by the spectrum of the standard star, extracted with the same extraction parameters applied to our target sources, and multiplying by its template (Cohen et al. 2003).

For sources with extended emission and spatial structure, the spectrum is the convolution of the source brightness distribution with the beam profile. In such a case a rigorous flux calibration requires a reliable model of the source geometry, and a characterization of the instru-

ment's beam profile. Since the beam profile, defined as the map obtained by moving a point-like source across the aperture and its variation with wavelength is not publicly documented yet, we did not apply any correction due to diffraction losses or gains in the slit that are inherent to extended sources. Because the wavelength dependence of such a correction may cause an additional slope in the observed spectra (Smith et al. 2004), we compared the extracted IRS fluxes with the measured IRAC and MIPS density fluxes for those galaxies that are listed in our sample and have broad-band observations available in the *Spitzer* public archive. Figure 3 shows the low resolution spectra of seven elliptical galaxies with data points from the four channels of the IRAC instrument and the MIPS $24\mu\text{m}$ channel. For each galaxy, the broad-band photometry, performed within a aperture equal to $r_e/8$, centered on the galactic nucleus, has been scaled to match the IRS spectrum at $8\text{ }\mu\text{m}$. The spectral slope in the $4\text{--}8\text{ }\mu\text{m}$ region, as derived by IRS and IRAC measurements, is in good agreement, giving us confidence in the accuracy of the extracted spectra; any correction due to diffraction losses is likely to fall inside the calibration errors of IRAC and MIPS observations that are of the order of 20%.

Fluxes and slopes that have been extracted from these spectra (shifted to $z = 0$) are given in Table 2, where the slope at $6\text{ }\mu\text{m}$ is given in column 3, and the wavelengths (μm), fluxes (mJy) and uncertainties (mJy) are given at four wavelengths. The uncertainties in the fluxes are only due to the statistical errors obtained in the data reduction process. The individual spectra, without the small redshift corrections, are shown in Figure 4.

5. RESULTS AND INTERPRETATION

The results of the infrared age indicators are discussed first, followed by a comparison with the ages that one infers from the observed values of M/L_B .

5.1. Ages from the Infrared Data

We begin by inspecting a single typical spectrum, NGC 584, which is compared to a single-epoch stellar population model (Figure 5). The models with ages of 5 Gyr or less are clearly ruled out and the $5.3\text{--}9.6\mu\text{m}$ continuum is best fit with the 14 Gyr model. None of the models are particularly accurate in reproducing the $10\text{--}21\mu\text{m}$ continuum, but the 14 Gyr spectrum appears to be the best. Narrow atomic emission lines from [Ne II $\lambda 12.8\mu\text{m}$] and [Ne III $\lambda 15.3\mu\text{m}$] are common features and will be discussed separately.

The other important spectral features that occur in this wavelength range are from PAH emission, where the strongest lines are usually at $7.7\text{ }\mu\text{m}$ and $11.3\text{ }\mu\text{m}$. One galaxy, NGC 4697, shows PAH emission that dominates the spectrum, making it nearly impossible to remove from the underlying stellar spectrum; this galaxy is excluded from study here but will be discussed elsewhere. The only other galaxy with detectable PAH emission is NGC 3379, but the lines are weak so the stellar spectrum can be analyzed. The $7.7\mu\text{m}$ feature can contaminate the $L(6\text{ }\mu\text{m})/L(8.3\text{ }\mu\text{m})$ ratio, which may have occurred in the case of NGC 3379.

For the 29 galaxies in the sample, their spectra show tremendous similarity (Figure 4). There is no obvious difference in the spectral energy distribution be-

tween galaxies that have young or old ages according to Trager et al. (2000). For example, none of the galaxies in the sample are similar to a 3 Gyr population, all appearing to be older populations (Figure 5). To quantify this, we use the $L(9.6 \mu\text{m})/L(6 \mu\text{m})$ ratio as an age indicator, as it has the greatest leverage on the age, is insensitive to the precise bands used to define the ratios, and has a typical uncertainty of 5-10%. The distribution of this ratio has a mean value of 0.580 ± 0.008 , where $\sigma = 0.041$ and for quartile points of 0.55-0.66 (Figure 6). According to the models of Piovan, this would imply a mean age of 13 Gyr and a range defined by the quartiles of 9-16 Gyr (Table 3). We are not confident that the models of Piovan have sufficient absolute accuracy, as some of the deduced ages are greater than the age of the universe, 13.5 Gyr for Λ -CDM universe with $H_0 = 70 \text{ km}^{-1} \text{ s}^{-1} \text{ Mpc}^{-1}$. This is due mostly to the many uncertainties still affecting the modeling of the low-mass AGB stars, which, at older ages, dominate the AGB population. Temi et al. (2005b) found a similar offset in the absolute calibration of the Piovan models when comparing broad-band mid-infrared ratios with the predicted flux ratios for a small sample of elliptical galaxies. If we were to shift the scale of Piovan such that the mean age is 10 Gyr, the range in $L(9.6 \mu\text{m})/L(6 \mu\text{m})$ implies an age range of 8-13 Gyr.

The inferred age range seems moderately restricted, but it is likely to be narrower since the uncertainties introduced by measurement error is similar to the sigma inferred from the distribution (see below). When the $L(9.6 \mu\text{m})/L(6 \mu\text{m})$ age indicator is compared to the ages of Trager, there is no correlation (Figure 7). This is to be expected if the values of $L(9.6 \mu\text{m})/L(6 \mu\text{m})$ are random scatter about a mean value, but it does pose a conflict between these two age indicators, discussed below. Finally, we find that there is no correlation between $L(9.6 \mu\text{m})/L(6 \mu\text{m})$ and M/L_B , which also is explained if the galaxies all have similar ages.

Potentially the second best of our infrared age indicators is the $6 \mu\text{m}$ spectral slope (Figure 8). The mean value is -0.95 and nearly all of the galaxies are within 2σ of this value, so a considerable amount of the range is due to measurement error. The conversion from slope to age may be somewhat incorrect since a slope of -0.95 corresponds to 14 Gyr, which is slightly greater than the age of the Λ -CDM universe. Assuming that the slopes are dominated by photon statistics, the observed distribution requires variation in the age distribution. If the true mean age is assumed to be 10 Gyr and the underlying age distribution is a Gaussian, its corresponding $\sigma \simeq 3$ Gyr. As with the above infrared age indicator, there is no correlation with the ages of Trager et al. (2000).

5.2. M/L as an age indicator

The property of a single stellar population that changes the most with age is the luminosity, so we can examine whether the ratio M/L contains useful age information and if the optical or infrared age indicators are related to M/L . The choice of L is not particularly important since most decline with age as t^{-1} , but here we choose L_B , where the models show that $L_B \propto t^{-0.95}$ in the age range of interest (Bruzual & Charlot 2003). The mass within r_e is proportional to $r_e \sigma^2$, and even the very thorough determination of the mass by the SAURON

effort (Cappellari et al. 2005) finds that this is a reasonable quantity to use (the difference in the mass between the two methods is small compared to the range of M/L in the sample). We use the value of M/L_B as given by Trager et al. (2000) but since this quantity is known to increase as $L_B^{1/4}$, we correct this quantity for this effect, normalizing the values of M/L_B at $B_{0T} = -21$ (this reduces the scatter in the ensuing figures). A plot of M/L_B vs the Trager ages shows a modest correlation, but a large amount of scatter (Figure 9). The data are inconsistent with the time evolution of a single-age population.

Another approach for obtaining ages is to assume that the shape of the mass distributions is similar between galaxies so that M/L_B translates into an age. For this approach to yield correct results, the dark matter to luminous matter ratio should be either small or constant, which appears to be the case (Kronawitter et al. 2000; Saglia et al. 2000; Thomas et al. 2005b). Also, a correct age determination would require that M/L_B should be dominated by a single age population. Inferring ages from their M/L_B values (using the calibration of Bruzual & Charlot 2003), the galaxies cluster in age at 8.0-12.4 Gyr (25% to 75% quartile ages) with a median at 9.4 Gyr and an effective sigma for the distribution of 2.8 Gyr (Figure 10; Table 3). The quantity M/L_B depends on r_e , σ^2 , M_B , metallicity and distance d , which each have an uncertainties and when added incoherently, leads to a typical uncertainty in an individual M/L_B of 25%, which would introduce an uncertainty in the age of about 2.5 Gyr. Therefore, much of the range of inferred ages may be related to observational uncertainties in determining M/L_B . There are a few galaxies with ages near 20 Gyr, one of which is the well-studied system NGC 1399, that is was also observed by Saglia et al. (2000). Using a detailed dynamical model, they found $M/L_B = 10$, which corresponds to an age of 13 Gyr. This points out that these large ages can be due to the uncertainties of the method in determining M/L_B .

5.3. Are there any young galaxies in this sample?

We have searched for the most likely young galaxies by examining those that have the youngest ages as given by Trager et al. (2000) and Thomas et al. (2005a), while also having low M/L_B and high $L(9.6 \mu\text{m})/L(6 \mu\text{m})$ ratios (Table 2, 3). Two galaxies fit that category, NGC 3377 and NGC 1700. For NGC 3377, Trager list an age of 3.7 Gyr, $M/L_B = 4.3$ (5.3 ± 1.3 Gyr), and $L(9.6 \mu\text{m})/L(6 \mu\text{m}) = 0.67 \pm 0.07$ (9 ± 2.5 Gyr). This galaxy is a relatively rapid rotator, so the mass may have been underestimated, which would raise M/L_B and the inferred age. There are no obvious signs of a recent merger in the structural properties of the galaxy (Schweizer & Seitzer 1992), and while the infrared ratio is higher than average, it is within 2σ of the mean and its nominal value, 9 Gyr, does not imply a young age. The evidence is not compelling for NGC 3377 being a young galaxy.

The other system, NGC 1700, has one of the youngest ages listed by Trager, 2.3 Gyr, and values for M/L_B and $L(9.6 \mu\text{m})/L(6 \mu\text{m})$ of 4.4 and 0.66 ± 0.07 ; also, the other two infrared ratios indicate a galaxy younger than the sample average. The age inferred from M/L_B is 5.5 ± 1.4 Gyr and the age inferred from the infrared ratio is 9.3 ($-1.5/+3$; it would be 1.5 Gyr younger if we were

to change the normalization so that the median galaxy age is 10 Gyr). The 3σ lower limit on the age from the infrared indicator is 4.8 Gyr (4.0 Gyr for the 10 Gyr median galaxy normalization). Other observers also suggest a young age, but not as young as the Trager value. Statler et al. (1996) suggests an age of 3-6 Gyr based on the extent of the region of relaxed dynamics near the center, while Schweizer & Seitzer (1992) give an age of 6 Gyr based on the galaxy color. The study of the globular cluster population (Whitmore et al. 1997) shows that it is typical of normal old ellipticals, where the population lies between the predictions for an old, metal-poor population (15 Gyr) and a solar metallicity population (5 Gyr). Using the same data from *HST* and ground-based data, Brown et al. (2000) show that the ages could be as low as 3 Gyr if the globular clusters have super-solar abundances, $[\text{Fe}/\text{H}] = +0.5$. The galaxy has a counter-rotating core and there is evidence of dust in the central region, also consistent with a merger, although the magnitude of the merger is poorly constrained. On balance, it seems likely that this is an intermediate age galaxy (4-8 Gyr), but it is unlikely to be as young as Trager suggests and it could be old, like the other galaxies.

6. DISCUSSION AND CONCLUSIONS

The ages deduced from the infrared spectra indicate an old mean age (10-13 Gyr) with a narrow age distribution of only a few Gyr. This is consistent with the ages inferred from the M/L_B distribution, as well as for the broadband flux age indicators (Temi et al. 2005a,b). These results would appear to be in conflict with the ages deduced by Trager from their optical line indices.

The ages determined here and by Trager are single-population ages, so we examine whether both methods are affected differently by multiple-age populations, in which case it would be possible to identify the contributions from multiple populations. There are an infinite number of ways of combining populations, so for simplicity, we use two populations, one being old (12 Gyr) and one being younger (1 Gyr). For this combination of populations, we calculate the effective age if one interpreted the result as a single-age population. For the optical line index ages and M/L_B , we use the on-line model of Worthey with Solar metallicities while for the infrared ages, we use the Solar metallicity Piovan models. As the fraction of the younger population is increased, the inferred age naturally decreases, with the M/L_B indicator least affected by the addition of a younger component, and the $\text{H}\beta$ age indicator being most strongly affected (Figure 11). The apparent age decreases by a factor of two with the addition of the 1 Gyr stellar component of 2.2%, 4.3%, and 9.8% (total mass) for the age indicators of $\text{H}\beta$, infrared, and M/L_B , respectively. In order for the inferred age to be greater than 10 Gyr, the young population can only account for 0.52%, 0.87%, and 2.1% of the total mass of the galaxy for the $\text{H}\beta$, infrared, and M/L_B age indicators. This is also consistent with the required mass fraction of young stars ($\sim 1\%$) as derived by the observed flux ratio $F(24\mu\text{m})/F(3.6\mu\text{m})$ when theoretical mid-infrared SSP models are combined (Temi et al. 2005b). A remarkable implication is that when the $\text{H}\beta$ indicators show a old age (e.g., 13 Gyr), it suggests that there has been virtually no star formation during the recent lifetime of the galaxy.

The general similarity between these three luminosity-weighted age indicators implies that there will be a strong correlation between the ages determined from the three methods. As discussed above, the uncertainties in the ages derived from the infrared and M/L_B methods are responsible for most of the observed range, so the lack of a correlation between the two methods is not surprising. However, the range of ages from the $\text{H}\beta$ age indicator is significantly larger than the errors, so finding a statistical correlation with the other quantities should be possible. There is no correlation of the $\text{H}\beta$ age indicators with the infrared indicators and the correlation with M/L_B is quite weak and of the wrong slope. Maraston & Thomas (2000) have shown that the addition of a small old metal-poor population can reduce the Hbeta ages of galaxies, but it is unclear if the addition of this type of population can reduce the ages to younger values given by Trager. We conclude that the introduction of a second, younger population will not lead to age determinations that are consistent between the $\text{H}\beta$ method and either the infrared method or the M/L_B method. The discrepancy with the Trager ages remains, indicating that either the infrared and M/L_B methods are flawed, or their approach is flawed. Trager have considered the prime candidates for contamination of $\text{H}\beta$ and shown them to be unimportant, or possible to correct for. Therefore, if their method is incorrect, there would have to be a very significant contamination channel that is not yet recognized. The problem does not lie with the method, because independent studies using line indices yield similar results (Denicoló et al. 2005a,b).

Insight into the formation ages of ellipticals can be obtained from studies of galaxies at higher redshifts, although the results are not entirely clear. There is broad agreement that at redshifts beyond $z=1$, and even $z > 2$, massive red (early-type) galaxies have little star formation present, indicating very old populations (Daddi et al. 2005,?; Labbé et al. 2005; Cappellari et al. 2005). For reference, redshifts of 0.5, 1.0, 2.0, and 3.0 correspond to ages of 5.0, 8.6, 10.3, and 11.4 Gyr in a Λ -CDM universe, while the age of the universe is 13.5 Gyr. Less massive galaxies appear to have more star formation (Treu et al. 2005), and if this aspect remains in the galaxies today, it might be seen in present day data. However, we find no correspondence between the Trager ages (or our IR ages) and the mass of our sample galaxies (Figure 12). Merging is likely to have occurred since $z = 1$ because the number of early-type galaxies has doubled since that time. In order not to produce galaxies that are too blue, star formation probably was not a significant part of these mergers (Bell et al. 2004, 2005; Faber et al. 2005). It is still unclear whether this degree of merging would destroy rather tight correlations, such as between velocity dispersion and Mg line strength. Finally, there needs to be an analysis as to whether the age distribution found by Trager is consistent with the observations at higher redshift and the expected mergers.

The calibration of the infrared spectral energy distributions is one of the important aspects of our technique that needs to be improved. Presently, we rely on the models of Piovan, which despite their sophistication, are the first to predict the level of detail that we utilize. As with all models, there are significant improvements that can and will be made in the future, and at some point, we hope

that the data and models are calibrated well-enough that we can make credible maximum likelihood fits between the two. As a complement to using improved models, we hope to use the infrared spectra of globular clusters with known ages and metallicities as the basis set for comparison with the data. This year, we have a program to observe a few globular clusters over a range of ages and metallicities, and this program holds the prospect of being able to make a comparison with the galaxies, leading to an independent age for these systems.

We would like to thank Scott Trager, Guy Worthey, Bill Mathews, Rebecca Bernstein, Doug Richstone, Jimmy Irwin, and Tom Roellig for their valuable comments and advice. Particular thanks are due to Lorenzo Piovan, who provided his models in digital form and was patient in explaining various details. Also, the on-line model of Worthey, at http://astro.wsu.edu/worthey/dial/dial_a_model.html were of great assistance. We would like to thank NASA for their financial support of Spitzer program 3535.

REFERENCES

- Bell, E. F., et al. 2004, *ApJ*, 608, 752
 Bell, E. F., et al. 2005, *ApJ*, 625, 23
 Bressan, A., Granato, G. L., & Silva, L. 1998, *A&A*, 332, 135
 Brown, R. J. N., Forbes, D. A., Kissler-Patig, M., & Brodie, J. P. 2000, *MNRAS*, 317, 406
 Bruzual, G., & Charlot, S. 2003, *MNRAS*, 344, 1000
 Cappellari, M., et al. 2005, *ArXiv Astrophysics e-prints*, arXiv:astro-ph/0505042
 Cohen, M., Wheaton, W. A., & Megeath, S. T. 2003, *AJ*, 126, 1090
 Daddi, E., et al. 2005, *ApJ*, 631, L13
 Daddi, E., et al. 2005, *ApJ*, 626, 680
 Decin, L., Morris, P. W., Appleton, P. N., Charmandaris, V., Armus, L., & Houck, J. R. 2004, *ApJS*, 154, 408
 Denicoló, G., Terlevich, R., Terlevich, E., Forbes, D. A., Terlevich, A., & Carrasco, L. 2005, *MNRAS*, 356, 1440
 Denicoló, G., Terlevich, R., Terlevich, E., Forbes, D. A., & Terlevich, A. 2005, *MNRAS*, 358, 813
 Faber, S. M., et al. 2005, *ArXiv Astrophysics e-prints*, arXiv:astro-ph/0506044
 Higdon, S. J. U., et al. 2004, *PASP*, 116, 975
 Houck, J. R., et al. 2004, *ApJS*, 154, 18
 Kauffmann, G., & Charlot, S. 1998, *MNRAS*, 294, 705
 Kronawitter, A., Gerhard, O. E., Saglia, R. P., & Bender, R. 2000, *ASP Conf. Ser.* 197: Dynamics of Galaxies: from the Early Universe to the Present, 197, 99
 Labbé, I., et al. 2005, *ApJ*, 624, L81
 Lançon, A., & Mouhcine, M. 2002, *A&A*, 393, 167
 Maraston, C., & Thomas, D. 2000, *ApJ*, 541, 126
 Meneux, B., et al. 2005, *ArXiv Astrophysics e-prints*, arXiv:astro-ph/0511656
 Mouhcine, M., & Lançon, A. 2003, *A&A*, 402, 425
 Piovan, L., Tantaló, R., & Chiosi, C. 2003, *A&A*, 408, 559
 Pipino, A., & Matteucci, F. 2005, *ArXiv Astrophysics e-prints*, arXiv:astro-ph/0510609
 Pipino, A., & Matteucci, F. 2003, *Ap&SS*, 284, 799
 Saglia, R. P., Kronawitter, A., Gerhard, O., & Bender, R. 2000, *AJ*, 119, 153
 Schweizer, F., & Seitzer, P. 1992, *AJ*, 104, 1039
 Smith, J. D. T., et al. 2004, *ApJS*, 154, 199
 Statler, T. S., Smecker-Hane, T., & Cecil, G. N. 1996, *AJ*, 111, 1512
 Tantaló, R., & Chiosi, C. 2004, *MNRAS*, 353, 917
 Temi, P., Mathews, W. G., & Brighenti, F. 2005, *ApJ*, 622, 235
 Temi, P., Brighenti, F., & Mathews, W. G. 2005, *ApJ*, 635
 Terlevich, A. I., & Forbes, D. A. 2002, *MNRAS*, 330, 547
 Thomas, D., Maraston, C., Bender, R., & de Oliveira, C. M. 2005, *ApJ*, 621, 673
 Thomas, J., Saglia, R. P., Bender, R., Thomas, D., Gebhardt, K., Magorrian, J., Corsini, E. M., & Wegner, G. 2005, *MNRAS*, 360, 1355
 Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, *AJ*, 120, 165
 Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, *AJ*, 119, 1645
 Treu, T., et al. 2005, *ApJ*, 633, 174
 Werner, M. W., et al. 2004, *ApJS*, 154, 1
 Worthey, G. 1994, *ApJS*, 95, 107
 Worthey, G., Faber, S. M., Gonzalez, J. J., & Burstein, D. 1994, *ApJS*, 94, 687
 Whitmore, B. C., Miller, B. W., Schweizer, F., & Fall, S. M. 1997, *AJ*, 114, 1797
 Yi, S. K., et al. 2005, *ApJ*, 619, L111

TABLE 1
SAMPLE GALAXIES AND OPTICAL PROPERTIES

No.	Name	B ₀ mag	r _e arcsec	μ_e	σ km s ⁻¹	Z _H	Err	cz km s ⁻¹	M-m mag	M _B mag	logM M _⊙	M/L _B M _⊙ /L _⊙	Age Gyr	Err Gyr
1	NGC 584	11.21	30	20.58	193	0.49	0.03	1866	31.6	-20.39	10.72	4.84	2.5	0.3
2	NGC 636	12.22	19	20.72	160	0.34	0.07	1860	32.45	-20.23	10.53	4.04	4.1	0.7
3	NGC 720	11.13	40	21.16	239	0.46	0.17	1741	32.29	-21.16	11.17	6.91	4.5	2.3
4	NGC 821	11.72	36	21.49	189	0.23	0.03	1730	31.99	-20.27	10.86	7.47	7.5	1.2
5	NGC 1339	12.5	17	20.64	158	0.12	0.07	1355	31.52	-19.02	10.28	6.28	12.7	4.8
6	NGC 1351	12.48	26	21.33	157	-0.1	0.05	1529	31.52	-19.04	10.46	7.65	17	3.3
7	NGC 1374	12.01	30	21.26	185	0.13	0.07	1349	31.52	-19.51	10.67	8.63	9.5	2.6
8	NGC 1379	11.87	42	21.79	130	-0.08	0.06	1360	31.52	-19.65	10.51	4.96	10.9	2.9
9	NGC 1399	10.44	42	20.68	375	0.29	0.06	1431	31.52	-21.08	11.43	14.85	11.5	2.4
10	NGC 1404	10.98	27	20.02	260	0.25	0.05	1923	31.52	-20.54	10.92	6.04	9	2.5
11	NGC 1427	11.81	33	21.34	175	-0.07	0.03	1416	31.52	-19.71	10.66	7.56	12.2	1.6
12	NGC 1453	12.26	28	21.47	286	0.32	0.06	3886	33.59	-21.33	11.43	10.34	7.6	1.9
13	IC 2006	12.25	29	21.45	136	0.06	0.06	1371	31.52	-19.27	10.39	5.75	16.9	4.2
14	NGC 1700	12.01	24	20.82	227	0.5	0.03	3895	33.31	-21.3	11.11	4.75	2.3	0.3
15	NGC 2300	11.77	34	21.42	252	0.38	0.05	1938	32.15	-20.38	11.12	12.25	5.9	1.5
16	NGC 3377	11.07	34	20.78	108	0.2	0.06	724	30.33	-19.26	10.02	2.89	3.7	0.8
17	NGC 3379	10.18	35	20.15	203	0.22	0.03	945	30.2	-20.02	10.55	5.88	8.6	1.4
18	NGC 4472	9.33	104	21.4	279	0.26	0.05	980	31.14	-21.81	11.49	7.67	7.9	1.7
19	NGC 4478	12.21	14	19.87	128	0.3	0.1	1365	31.37	-19.16	9.99	2.64	4.6	2.3
20	NGC 4552	10.57	30	20.22	252	0.28	0.04	364	31.01	-20.44	10.83	7.77	10.5	1.2
21	NGC 4649	9.7	74	21.11	310	0.29	0.04	1117	31.21	-21.51	11.45	9.87	11.7	1.5
22	NGC 5638	12.06	34	21.58	154	0.2	0.03	1649	32.18	-20.12	10.7	5.23	8.3	1.4
23	NGC 5812	11.83	22	20.65	200	0.39	0.04	1929	32.23	-20.4	10.74	5.65	5.3	1.1
24	NGC 5813	11.42	49	21.83	205	-0.03	0.03	1954	32.62	-21.2	11.19	6.61	18.3	2.3
25	NGC 5831	12.31	27	21.44	160	0.54	0.03	1655	32.25	-19.94	10.64	6.05	2.6	0.3
26	NGC 5846	10.91	83	22.26	224	0.15	0.05	1714	32.06	-21.15	11.38	8.96	13.5	3.3
27	NGC 6703	11.97	24	20.88	183	0.32	0.06	2403	32.18	-20.21	10.69	5.49	4.3	0.7
28	NGC 7562	12.37	25	21.28	248	0.21	0.04	3608	33.87	-21.5	11.31	6.42	7.6	1.6
29	NGC 7619	11.93	32	21.52	300	0.21	0.03	3762	33.7	-21.77	11.55	9.91	14.4	2.2

TABLE 2
MID-INFRARED FLUXES AND SLOPES

No.	Name	$\alpha(6\mu\text{m})$	Err	λ_1	$F_{\nu,1}$	Err	λ_2	$F_{\nu,2}$	Err	λ_3	$F_{\nu,3}$	Err	λ_4	$F_{\nu,4}$	Err	$F_{\nu,3}/F_{\nu,1}$	Err
1	NGC 584	-0.98	0.11	5.81	26.7	0.1	8.32	13.8	0.5	9.92	15.2	0.2	12.98	12.3	0.2	0.57	0.007
2	NGC 636	-1.51	0.37	5.85	13.0	0.2	8.32	7.5	0.3	9.92	7.2	0.2	12.98	5.4	0.1	0.56	0.016
3	NGC 720	-0.83	0.24	5.91	25.7	0.1	8.32	14.5	0.2	9.92	16.2	0.1	12.98	12.7	0.1	0.63	0.006
4	NGC 821	-0.63	0.16	5.85	18.0	0.1	8.32	9.1	0.3	9.92	10.6	0.1	12.98	7.4	0.1	0.59	0.009
5	NGC 1339	-0.73	0.31	5.82	15.5	0.2	8.32	8.6	0.2	9.92	8.9	0.1	12.98	6.3	0.1	0.57	0.011
6	NGC 1351	-0.78	0.20	5.82	11.9	0.2	8.30	6.8	0.3	9.92	6.5	0.1	12.95	4.7	0.1	0.55	0.011
7	NGC 1374	-0.79	0.22	5.82	15.6	0.1	8.32	9.3	0.2	9.92	9.2	0.1	12.98	7.1	0.1	0.59	0.007
8	NGC 1379	-0.62	0.25	5.82	10.3	0.2	8.32	6.2	0.2	9.92	6.0	0.1	12.98	4.3	0.1	0.59	0.016
9	NGC 1399	-0.91	0.10	5.82	42.5	0.2	8.32	21.7	0.2	9.92	25.3	0.1	12.98	19.8	0.1	0.59	0.004
10	NGC 1404	-1.01	0.10	5.82	43.6	0.2	8.30	24.3	0.2	9.92	27.1	0.1	12.98	21.0	0.1	0.62	0.004
11	NGC 1427	-0.74	0.25	5.82	13.1	0.2	8.30	7.3	0.2	9.92	8.0	0.1	12.98	5.4	0.1	0.61	0.011
12	NGC 1453	-1.58	0.31	5.88	17.6	0.1	8.32	9.5	0.1	9.92	10.1	0.1	12.98	8.9	0.1	0.57	0.007
13	IC 2006	-1.31	0.22	5.79	11.3	0.2	8.32	6.1	0.2	9.92	6.3	0.1	12.98	4.8	0.1	0.55	0.012
14	NGC 1700	-0.76	0.19	5.83	18.3	0.2	8.35	11.4	0.0	9.92	12.1	0.2	12.98	8.7	0.1	0.66	0.011
15	NGC 2300	-0.74	0.19	5.82	19.8	0.2	8.32	10.7	0.2	9.92	11.8	0.1	12.98	9.0	0.1	0.60	0.009
16	NGC 3377	-1.04	0.23	5.85	26.9	0.2	8.32	15.8	0.3	9.92	18.0	0.1	12.98	12.8	0.1	0.67	0.007
17	NGC 3379	-0.47	0.11	5.92	49.2	0.3	8.32	33.8	0.2	9.92	32.2	0.2	12.98	21.8	0.1	0.65	0.005
18	NGC 4472	-1.04	0.07	5.82	48.0	0.2	8.32	25.7	0.2	9.92	29.4	0.1	12.98	22.8	0.1	0.61	0.003
19	NGC 4478	-1.34	0.24	5.82	15.3	0.2	8.32	7.6	0.2	9.92	7.8	0.1	12.98	6.1	0.1	0.51	0.007
20	NGC 4552	-1.19	0.14	5.82	45.6	0.2	8.32	24.5	0.3	9.92	26.9	0.2	12.98	21.4	0.1	0.59	0.004
21	NGC 4649	-0.96	0.11	5.82	36.5	0.2	8.32	20.6	0.2	9.93	23.4	0.1	12.98	18.3	0.1	0.64	0.005
22	NGC 5638	-0.66	0.28	5.82	12.1	0.2	8.32	7.2	0.2	9.92	7.4	0.2	12.97	5.2	0.1	0.61	0.016
23	NGC 5812	-0.36	0.18	5.85	21.0	0.2	8.32	13.0	0.4	9.90	11.6	0.1	12.98	9.7	0.1	0.55	0.008
24	NGC 5813	-0.79	0.11	5.82	21.0	0.1	8.29	10.4	0.1	9.93	11.3	0.1	12.98	8.5	0.1	0.54	0.007
25	NGC 5831	-1.46	0.26	5.82	11.9	0.1	8.32	6.4	0.2	9.92	6.8	0.1	12.98	5.5	0.1	0.57	0.012
26	NGC 5846	-1.03	0.18	5.82	18.9	0.2	8.32	12.0	0.2	9.92	12.1	0.1	12.98	9.5	0.1	0.64	0.007
27	NGC 6703	-1.25	0.24	5.85	16.4	0.1	8.32	8.4	0.3	9.92	9.9	0.1	12.98	7.9	0.1	0.61	0.009
28	NGC 7562	-0.49	0.31	5.82	13.9	0.1	8.32	7.9	0.2	9.92	7.5	0.1	12.98	4.8	0.1	0.54	0.008
29	NGC 7619	-1.50	0.20	5.82	18.4	0.2	8.32	10.6	0.2	9.92	10.1	0.1	12.98	8.1	0.0	0.55	0.009

TABLE 3
DERIVED AGES OF GALAXIES

No.	Name	t(Trager) Gyr	Err Gyr	t(Thomas) Gyr	Err Gyr	M/L _{B,cor} M _⊙ /L _⊙	t(M/L _B) Gyr	t(IR) Gyr
1	584	2.5	0.3	2.8	0.3	5.6	7.0	14.6
2	636	4.1	0.7	4.4	0.6	4.8	6.0	15.9
3	720	4.5	2.3	5.4	2.4	6.7	8.4	10.8
4	821	7.5	1.2	8.9	1.2	8.8	11.4	13.2
5	1339	12.7	4.8			9.9	12.8	14.4
6	1351	17	3.3			12.0	15.7	16.4
7	1374	9.5	2.6			12.2	15.9	13.4
8	1379	10.9	2.9			6.8	8.6	13.4
9	1399	11.5	2.4			14.6	19.3	12.9
10	1404	9	2.5			6.7	8.5	11.2
11	1427	12.2	1.6			10.2	13.2	12.0
12	1453	7.6	1.9	9.4	1.6	9.6	12.4	14.4
13	IC 2006	16.9	4.2			8.6	11.0	16.1
14	1700	2.3	0.3	2.6	0.3	4.4	5.5	9.3
15	2300	5.9	1.5	7.3	1.5	14.1	18.7	12.8
16	3377	3.7	0.8	3.6	0.5	4.3	5.3	8.9
17	3379	8.6	1.4	10	1.1	7.4	9.4	9.6
18	4472	7.9	1.7	9.6	1.4	6.4	8.0	11.7
19	4478	4.6	2.3	5.3	1.2	4.0	5.0	20.6
20	4552	10.5	1.2	12.4	1.5	8.8	11.4	13.2
21	4649	11.7	1.5	14.1	1.5	8.8	11.3	10.2
22	5638	8.3	1.4	9.5	0.9	6.4	8.1	12.0
23	5812	5.3	1.1	6.5	1	6.5	8.2	16.0
24	5813	18.3	2.3	16.6	2.2	6.3	8.0	17.4
25	5831	2.6	0.3	3	0.4	7.7	9.9	14.4
26	5846	13.5	3.3	14.2	2.2	8.7	11.1	10.1
27	6703	4.3	0.7	4.8	0.8	6.6	8.3	12.2
28	7562	7.6	1.6	8.6	1.3	5.7	7.2	17.6
29	7619	14.4	2.2	15.4	1.4	8.3	10.6	16.4

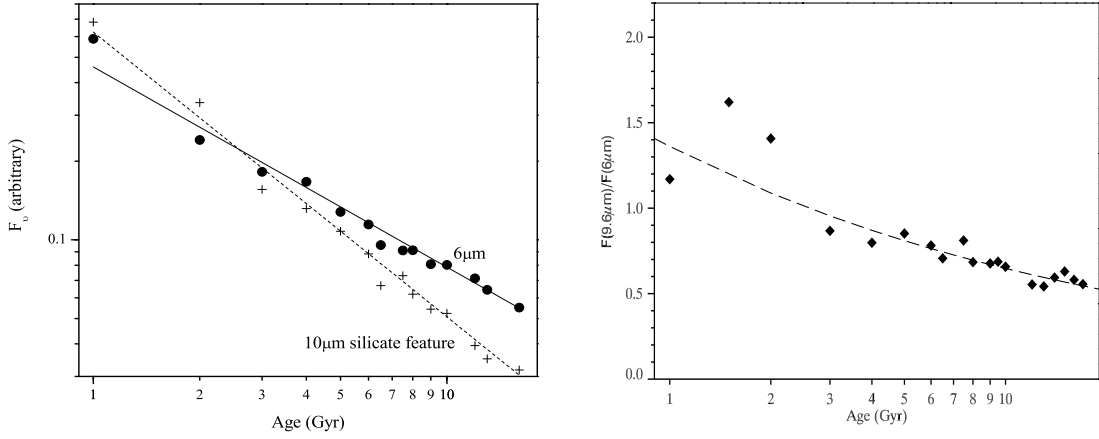


FIG. 1.— Left Panel shows the decline of the $6\mu\text{m}$ and the $9.6\mu\text{m}$ luminosities as a function of time for single-age populations, based on the solar metallicity models of Piovan et al. (2003), shown as data points. Because the silicate feature decreases more rapidly with time, the ratio of these luminosities forms an age indicator. The evolution of the ratio $F(9.6\mu\text{m})/F(6\mu\text{m})$ as a function of age for a single stellar population with metallicity $Z=0.02$ is presented in the right panel. The dashed line represent the relation between the flux ratio and the age t ($t = 2.6 (F(9.6\mu\text{m})/F(6\mu\text{m}))^{-3.1}$ Gyr).

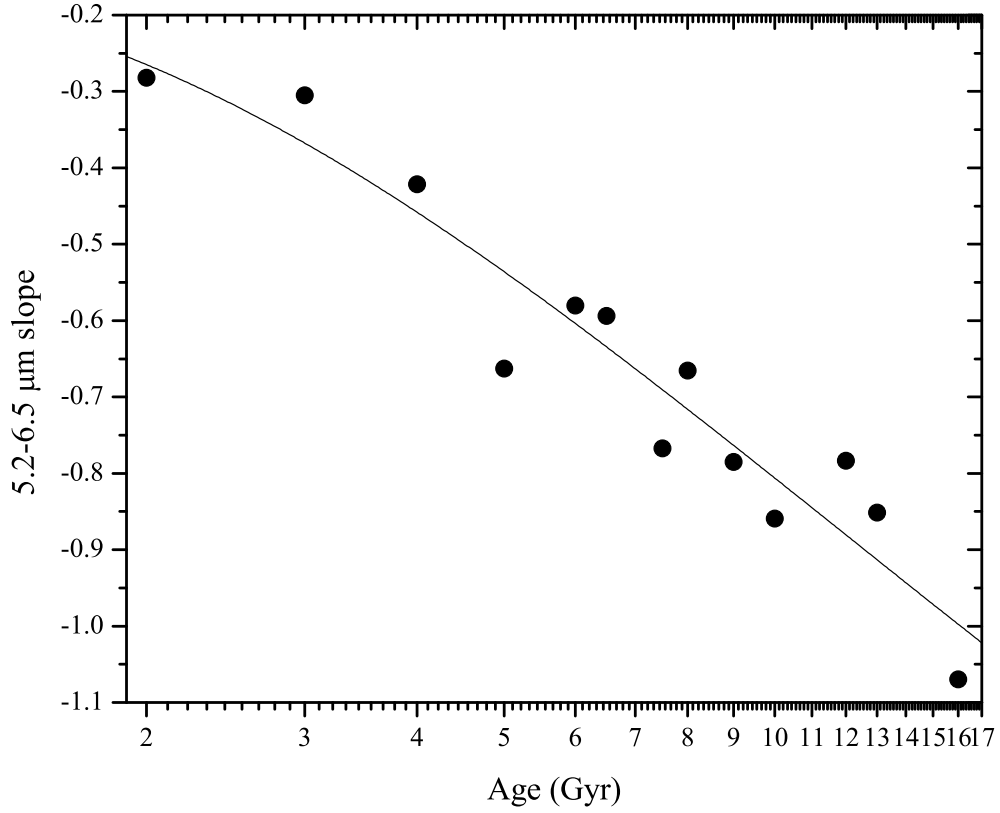


FIG. 2.— The slope near $6\mu\text{m}$ decreases with age in the solar metallicity single-age populations of Piovan et al. (2003), shown as solid points. A third-order polynomial is fit to the data.

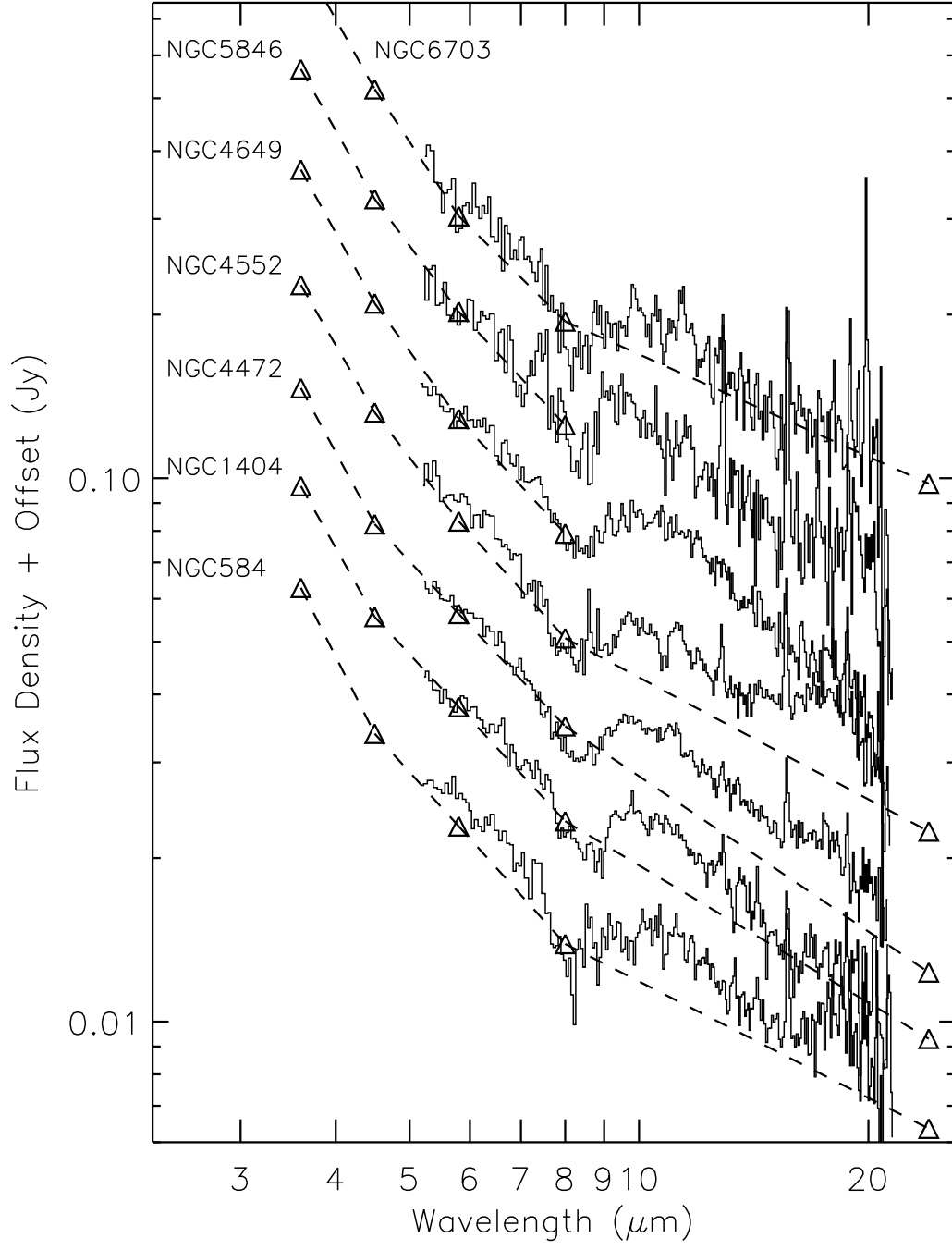


FIG. 3.— IRS low resolution spectra (solid line) of elliptical galaxies are presented along with IRAC and MIPS broad-band photometric data (triangles connected with dashed line). Spectra have been divided by arbitrary factors for clarity and the broad-band data are scaled to match the spectra at $8\mu\text{m}$. There is general agreement between the photometry and the spectral energy densities.

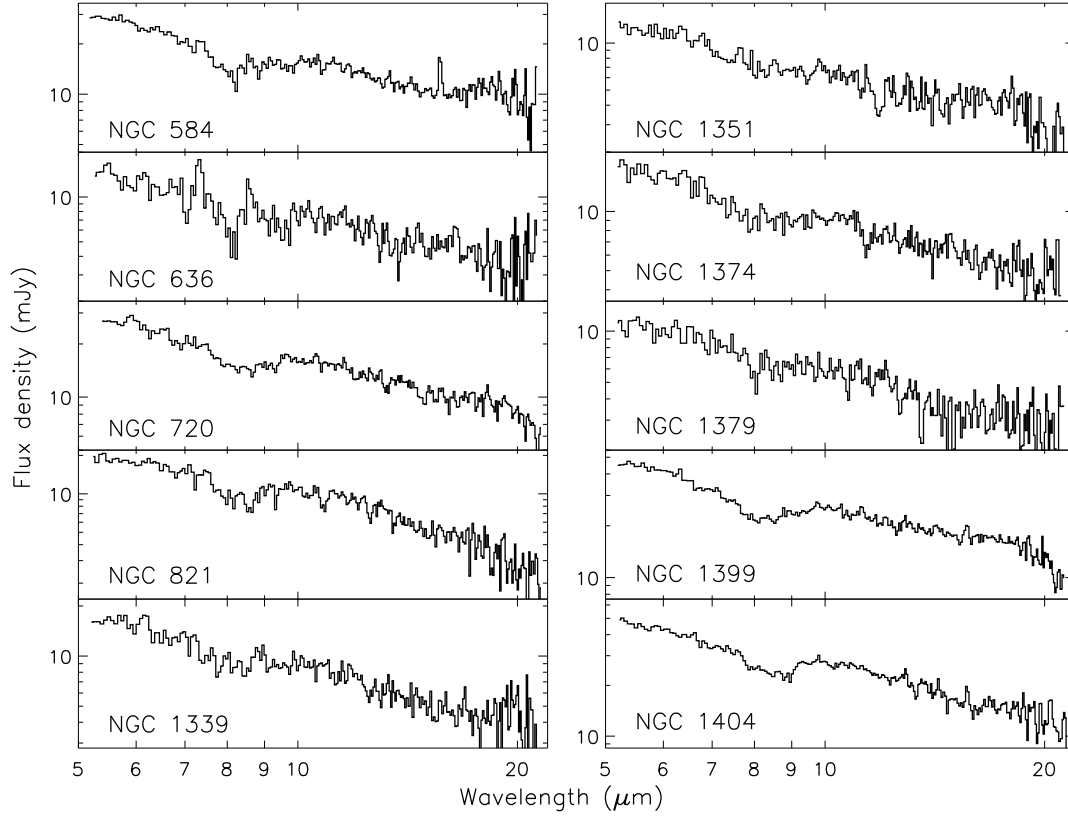


FIG. 4.— The flux density as a function of wavelength as obtained with the *IRS* on the *Spitzer Observatory*. The signal-to-noise is generally poor at the longest wavelengths.

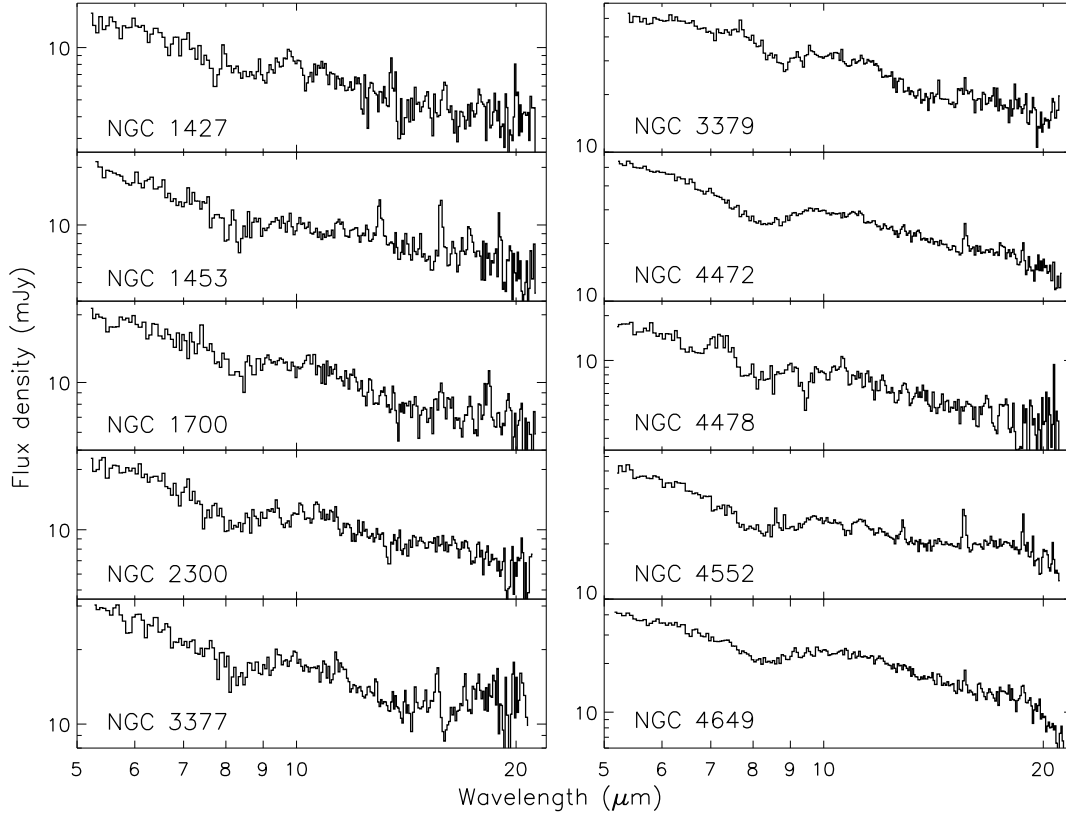


Fig. 4. — Continued.

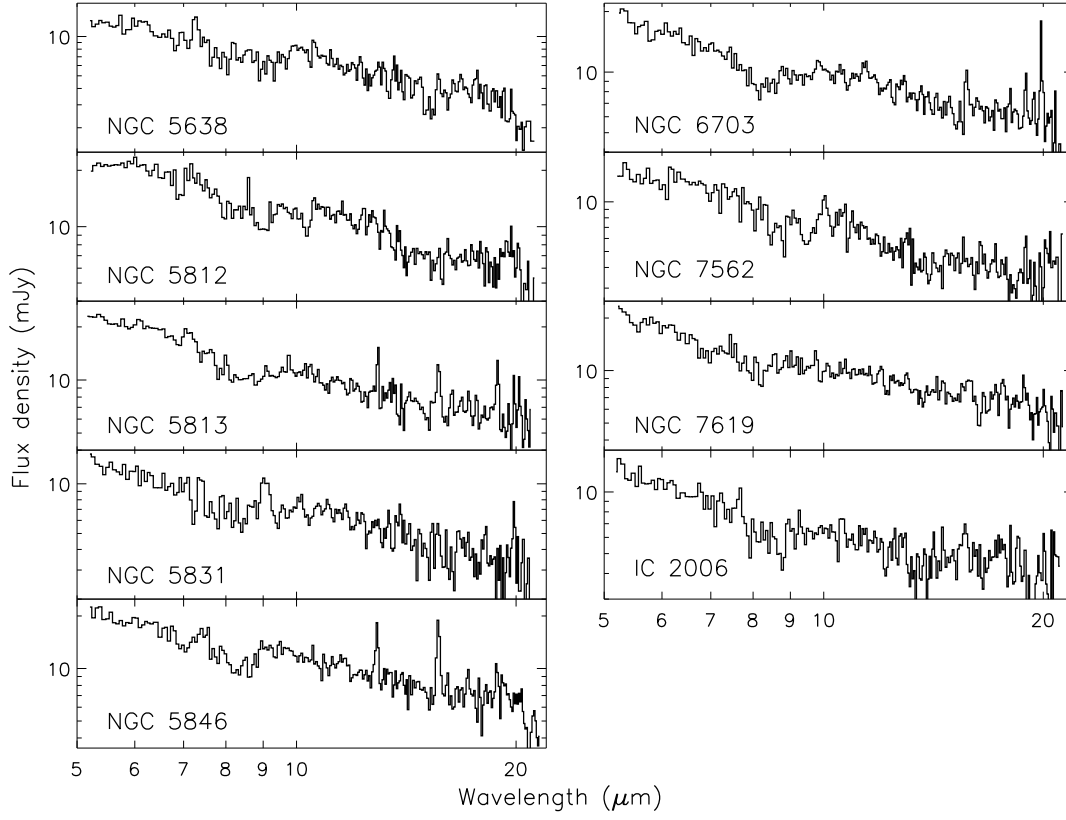


Fig. 4. — Continued.

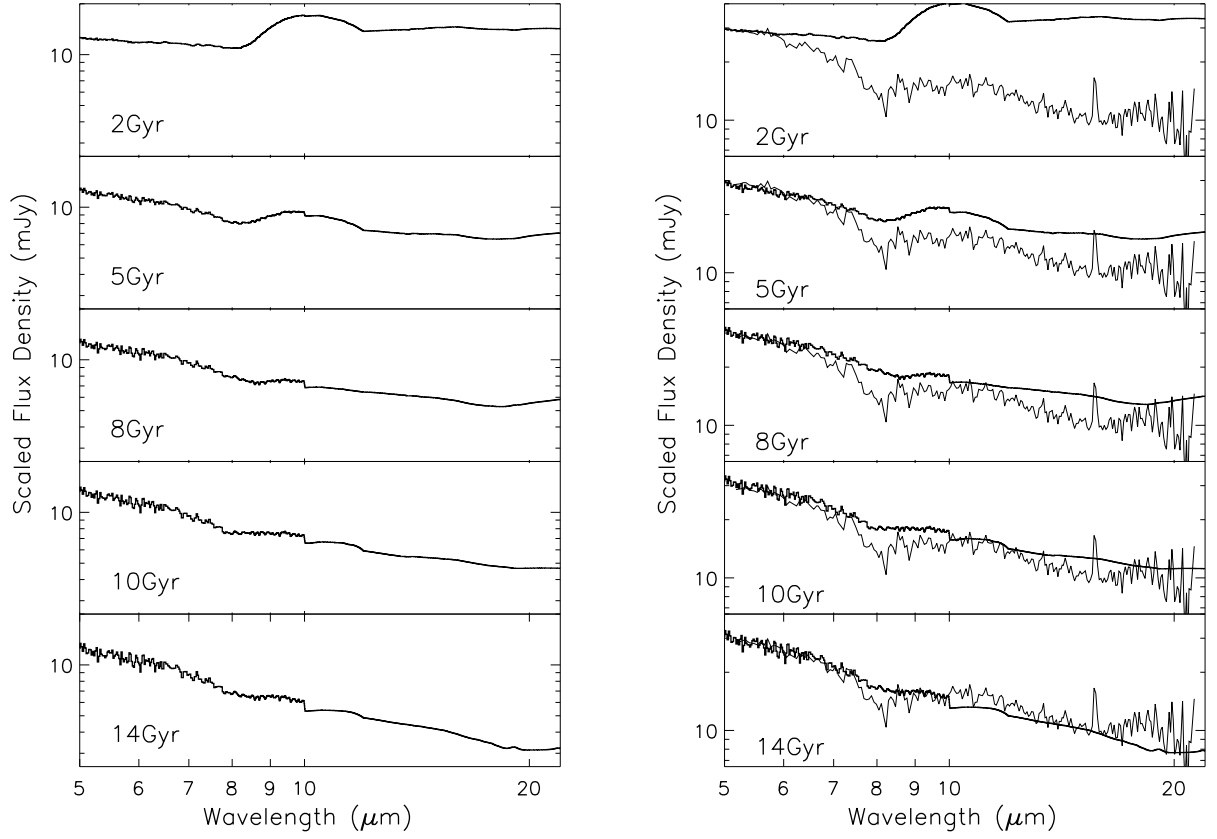


FIG. 5.— The flux density of the spectral models of Piovan et al. (2003) for a single-age stellar population and at solar abundances (left panel) shows the spectral steepening with age and the weakening of the $10\ \mu\text{m}$ silicate feature. A comparison between these same models and the galaxy NGC 584 is shown in the right panel. The best-fit appears to lie between 10 Gyr and 14 Gyr, in conflict with the age derived from the optical absorption line indices of 2.5 ± 0.3 Gyr.

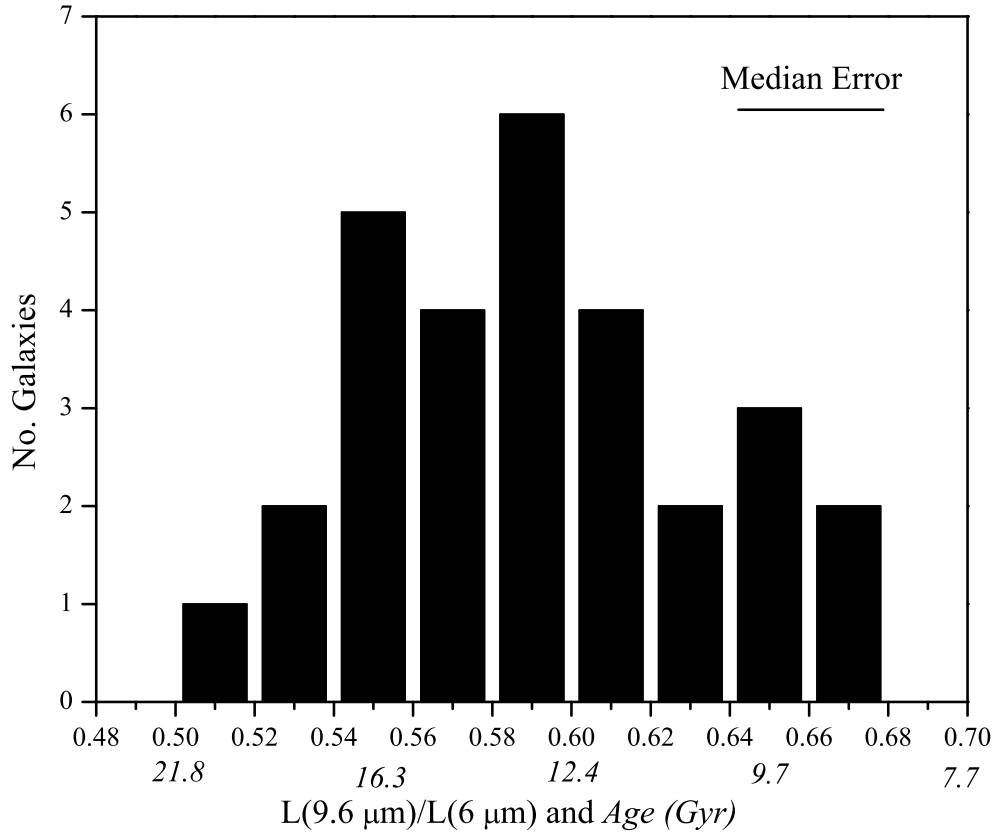


FIG. 6.— The distribution of the ratio $L(9.6 \mu\text{m})/L(6 \mu\text{m})$, with the corresponding age, derived from Piovan et al. (2003) along the bottom in italics. The mean ratio corresponds to an age of 13 Gyr and a σ of about 3 Gyr, but much of that range is due to uncertainties in the measurements, where the median error is shown.

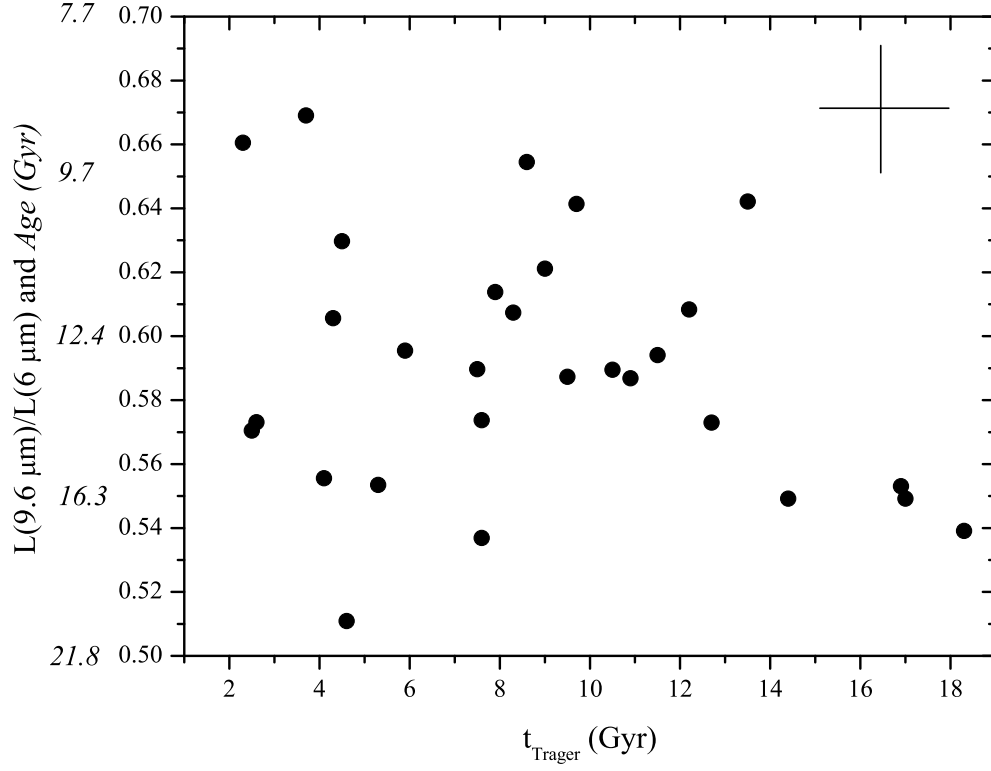


FIG. 7.— The infrared indicator (and inferred ages in italic) vs the ages from Trager et al. (2000) with average error bars in the upper right. The range in ages from infrared data is much narrower than from the optical data and there is no correlation between the two quantities.

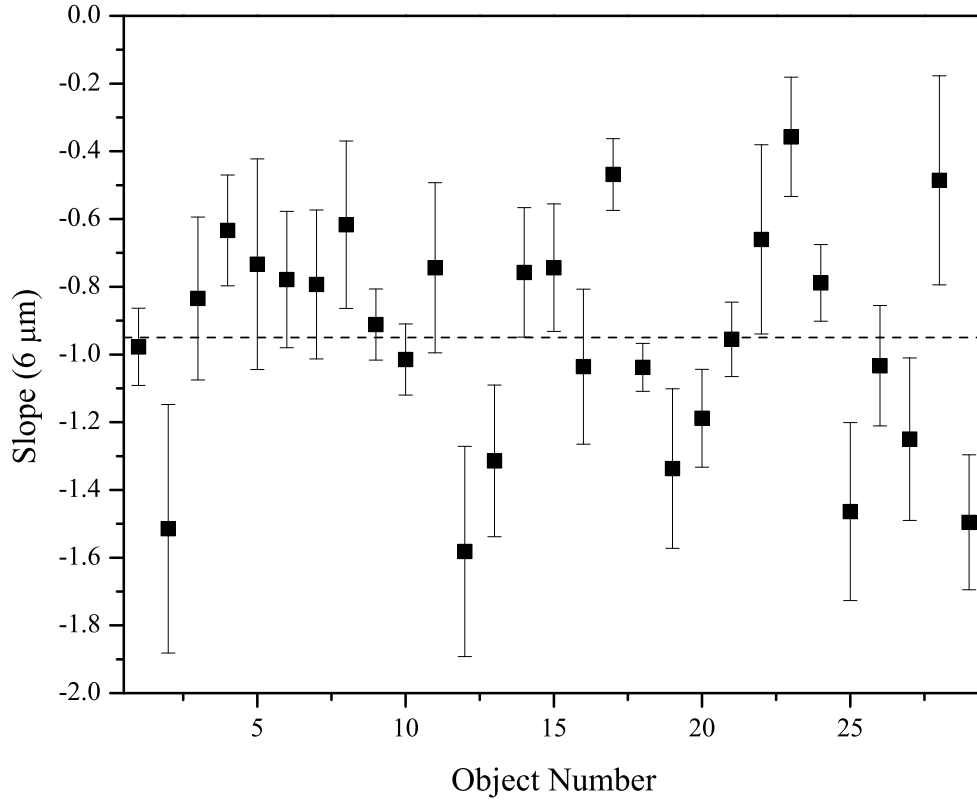


FIG. 8.— The $6\ \mu\text{m}$ spectral slope for objects by increasing RA, including the statistical uncertainties and the mean value. The mean value of -0.95 (the dashed line) corresponds to 14 Gyr. If systematic errors are smaller than statistical errors, some variation in ages is required, a result driven by a few objects with small errors.

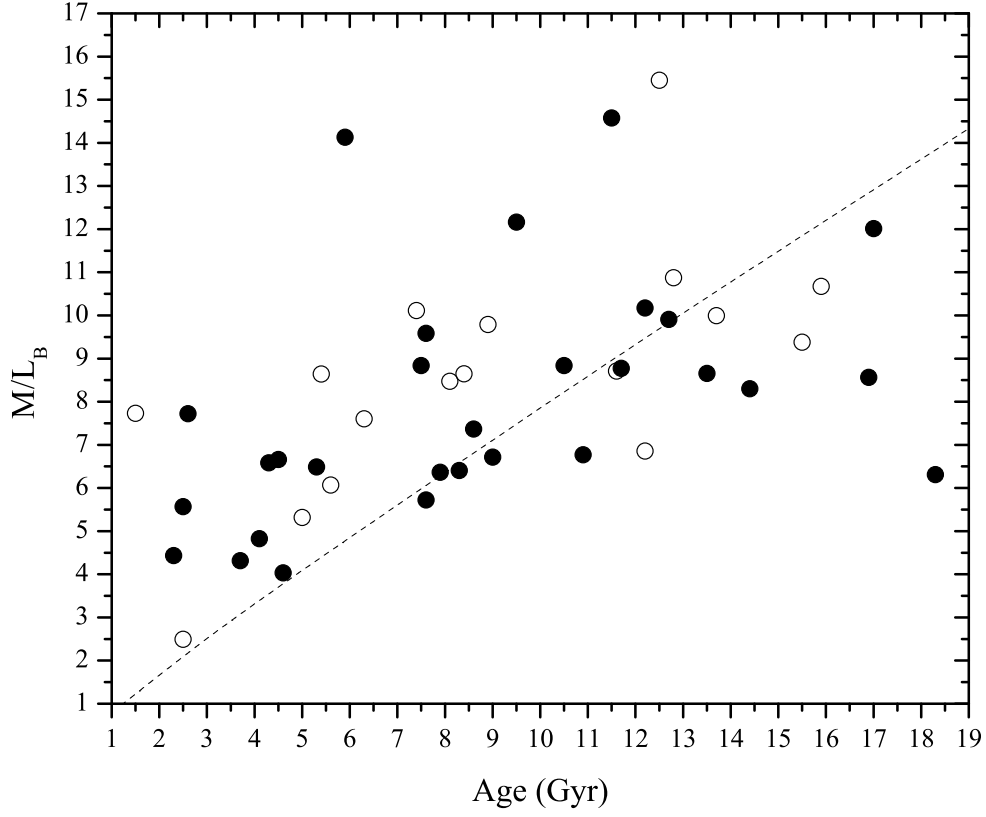


FIG. 9.— The value of M/L_B as a function of the ages from Trager et al. (2000), with the objects in our sample as black circles; M/L_B has been corrected for the luminosity dependence of the fundamental plane (normalized to $M_B = -21$). The open circles are the additional objects given by Trager et al. (2000), with the exception of M31 and M32. The solid line is the evolution of a single-age population with time. While there are slightly more objects in the low-age, low- M/L_B part of the figure, in general, there is almost no relationship between M/L_B and age.

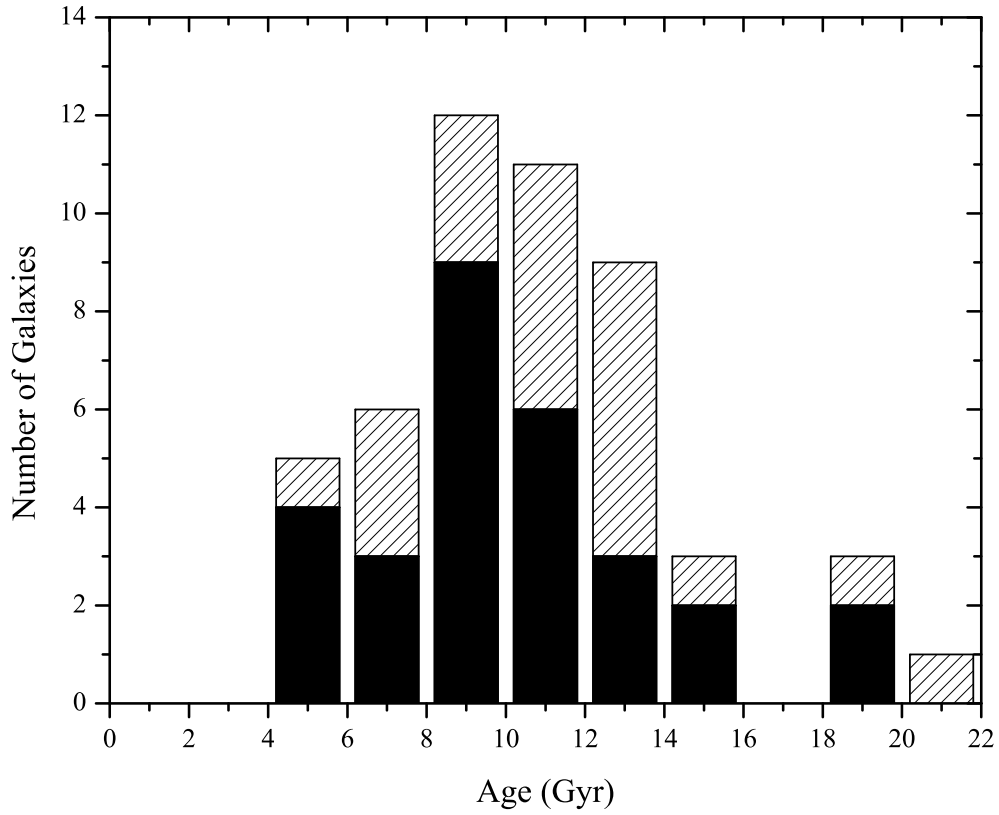


FIG. 10.— The ages derived from M/L_B given by Trager et al. (2000), after correcting it for the luminosity dependence of the fundamental plane. The solid bars are the galaxies in this sample while the hatched regions are the other objects in the list of Trager et al. (2000), with M31 and M32 excluded. The distribution is similar to a Gaussian with a peak at 10.1 Gyr (± 0.4 Gyr) and $\sigma = 2.8$ Gyr (± 0.5 Gyr), excluding the outliers at 20 Gyr. Most of this spread can be accounted for by measurement error.

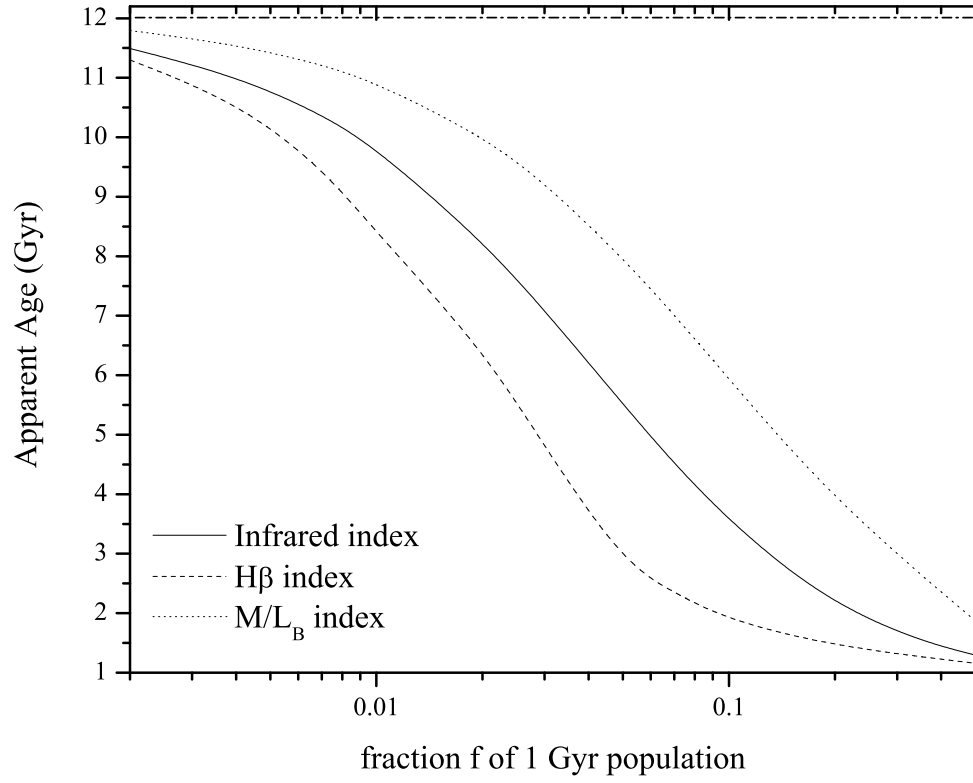


FIG. 11.— Two populations are combined, the older one being 12 Gyr (dot-dash line at top) and the other being a 1 Gyr population. The Apparent Age is the value one would infer by interpreting the mixed population as a single population. Ages inferred from the infrared index (solid line), the optical H β line, and M/L_B are shown for a solar metallicity model.

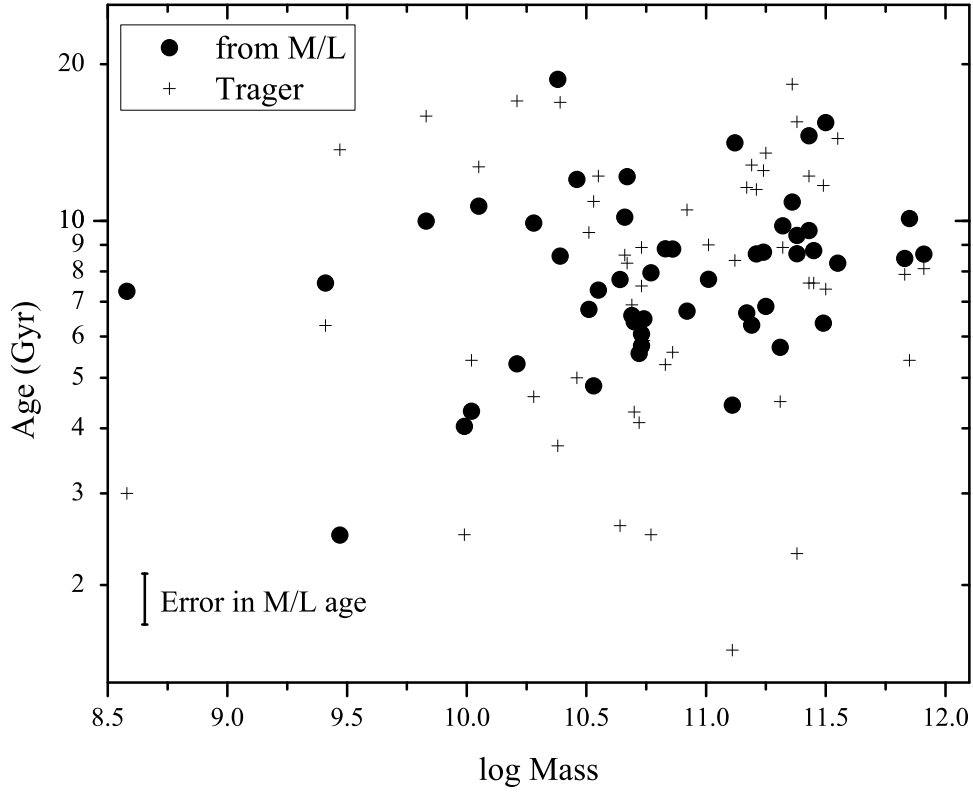


FIG. 12.— The ages given by Trager et al. (2000) and derived from M/L_B as a function of galaxy mass for 49 galaxies in the original survey, excluding M31 and M32. Neither group shows a correlation with mass. Based on the Trager ages, young galaxies occur at all mass scales.